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Solid phase recrystallization induced by nanosecond pulsed laser

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Abstract

In this work, it is demonstrated that UV nanosecond laser annealing can be used for solid phase recrystallization of pre-amorphized doped SOI structures. It is evidenced that using assisted heating (chuck at 450°C) sub-melt multipulse laser conditions allow the perfect crystal recovery of implanted Si. The recrystallization rate is also calculated.

1. Introduction

The use of UV nanosecond laser annealing (UVNLA) is a very attractive alternative to conventional furnace methods. Actually, the very low absorption depth and the extremely fast laser matter interaction, permits the use of the UVNLA when very low thermal budgets must be respected, e.g., 3D-sequential integration [1]. Most of processes using this technique deal with liquid phase recrystallization. In this paper, we will investigate solid phase recrystallization using multi-pulse UVNLA within an overall thermal budget compatible with 3D-sequential integration.

2. Experimental Procedure

Blanket SOI 300 mm wafers with top silicon layer of 22 nm and buried oxide (Box) of 20 nm were used as starting material for this study. After surface cleaning, 3 wafers were ion implanted in order to create an ultrathin amorphous layer (<20 nm). Implantation conditions are described in Table 1. Afterwards, samples were submitted to UVNLA using a SCREEN LT3100 platform based on a XeCl excimer laser (λ=308 nm) with a pulse duration of 160 ns. Several 15x15 mm² regions were irradiated with a single pulse and an increasing laser energy density ranging from 0.36 up to 1.80 J/cm² while the wafer temperature was maintained at 450°C thanks to a heating chuck. For the second part of the study, multi-pulse laser treatments were also performed. The use of an in-situ metrology based on a 635 nm wavelength laser Time Resolved Reflectometry (TRR), allows recording the reflected light intensity from the annealed surface during the UVNLA process. This in-situ metrology is used to detect the phase change of the near surface material, a-Si layer in our case. Actually, the reflected light intensity increases dramatically when the silicon layer melts.

Table 1: Ion implantation conditions leading to the formation of an amorphous layer in the near surface region.

Dopant	Energy [eV]	Dose [at/cm²]	a-Si thick. [nm]
As	9	1E15	17.0 ± 0.4
P	4	1E15	10.5 ± 0.4
B (PAI Ge)	6 (7)	1E15 (5E15)	11.8 ± 0.4

It permits clearly identifying transitions thresholds depending on the irradiated energy density, e.g., the explosive melt of the amorphous layer [1] or the total melt of the SOI layer.

3. Results and discussion

The laser pulse profile and measured TRR intensity during UVNLA process are presented in Fig.1. At low energy densities (ED) such as 600 mJ/cm², almost no evolution is observed. Only a weak increase of the TRR value is noted, most likely related to the temperature increase in the sample. For higher EDs (≥ 700 mJ/cm²), two characteristic features can be observed. The first peak (a) in Fig. 1 corresponds to the explosive melt and the second one (b) to the melt of the poly-Si obtained after explosive recrystallization [3]. Explosive melt threshold has been found to be around 680 mJ/cm² for all of samples described above.

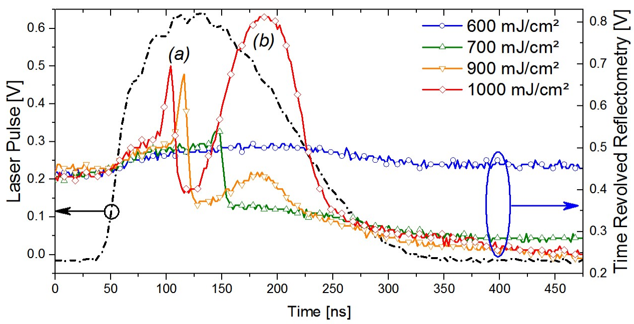

Fig. 1 Laser pulse (left axis) and time resolved reflectometry (TRR) profiles (right axis) recorded during the UVNLA process. Data for arsenic implanted SOI sample laser annealed at various energy densities. Labelled peaks correspond to (a) the explosive melt and (b) the 'second' melt.

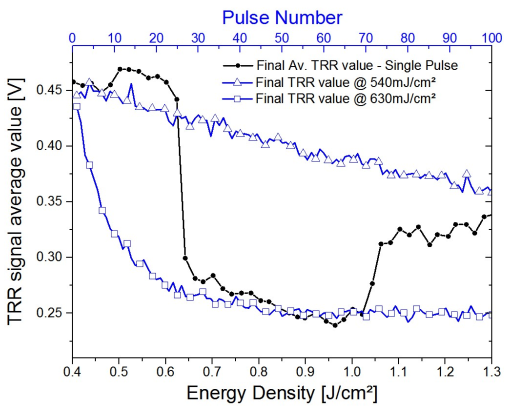

Fig. 2 TRR signal final average (○ bottom axis) as a function of the energy density using a single pulse irradiation, and TRR final value evolution as a function of the number of pulses with sub-melt laser conditions (□ and Δ, top axis). Arsenic implanted SOI.

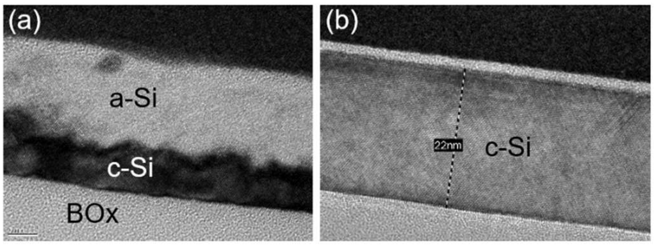

Fig. 3 Cross sectional TEM observations of 22 nm thick SOI structures (a) as-Arsenic-implanted and (b) after sub-melt multi pulse UVNLA (100 cumulative pulses at 630 mJ/cm²)

After identification of the explosive melt threshold, sub-melt multi-pulse irradiation conditions were explored for solid phase epitaxial recrystallization. About 200 ns after the end of the laser pulse, TRR signal becomes stable at a 'final' value.. The evolution of the final TRR value can be plotted as a function of ED. In case of single pulse (see Fig. 2 solid points), for low ED, the TRR value is close to the initial one (0.45 V see Fig. 1 right axis). Then, for ED higher than the explosive melt threshold, the TRR final value drops to 0.25 V. Finally, for ED higher than 1.05 J/cm², the TRR final value increases to 0.35 V. In a previous work [4] we showed that UVNLA process with ED higher than 1.00 J/cm² provokes the melt of the entire crystalline seed leading to poly-Si layer. For EDs lower than that and higher than the explosive melt threshold, a liquid phase recrystallization from the crystalline seed leads to a perfectly recrystallized Si layer. It means that TRR final value of 0.25 V corresponds to a perfectly recrystallized 22 nm thick SOI layer. Nevertheless, for energy densities lower than the explosive melt threshold, there is almost no evolution of the TRR value. Additionally, TEM observations (not presented here) prove that the a-Si layer remains amorphous after single pulse UVNLA process, confirming that using single pulse UVNLA below the melt threshold is not able to perform solid phase recrystallization.

Hence, multi-pulse sub-melt UNVLA process was explored using EDs lower than explosive threshold. Fig. 2 shows the evolution of the TRR value for multi-shots laser

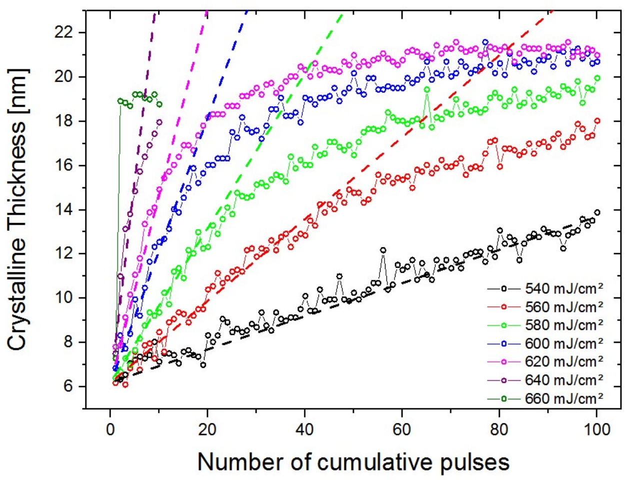

Fig. 4 Crystalline Si thickness versus number of pulses, for As-implanted SOI sample, as extracted from the TRR evolution measured during the laser processing

annealing (open symbols). It reveals a progressive drop of the TRR value down to 0.25 V, which corresponds to the perfectly recrystallized sample. Cross sectional TEM observations, shows that using 100 cumulated laser pulses at 630 mJ/cm² leads to a total crystal recovery of the implanted amorphous Si layer (see Fig.3). TRR signal dependence on pulse count clearly shows that the combination of multi-pulse and heating chuck leads to the progressive solid phase recrystallization of the amorphous layer from the crystalline seed.

In order to determine the recrystallization rate, the thickness of the crystalline seed is plotted versus the number of shots for different energies in Fig. 4. To do so, the reflectivity has been extracted from the TRR assuming a linear relationship. Then the thickness of a-Si and c-Si layer in the stack has been calculated from reflectivity using Fresnel equations for each TRR value. In Fig. 4, we observe a strong increase of the recrystallization rate when increasing ED.

Based on this methodology, the recrystallization rate evolution as a function of ED is plotted in Fig.5 for samples implanted with As, P and B. It shows an exponential evolution. A recrystallization rate of 1.5 nm/pulse can be obtained which is extremely fast considering the pulse duration (160 ns).

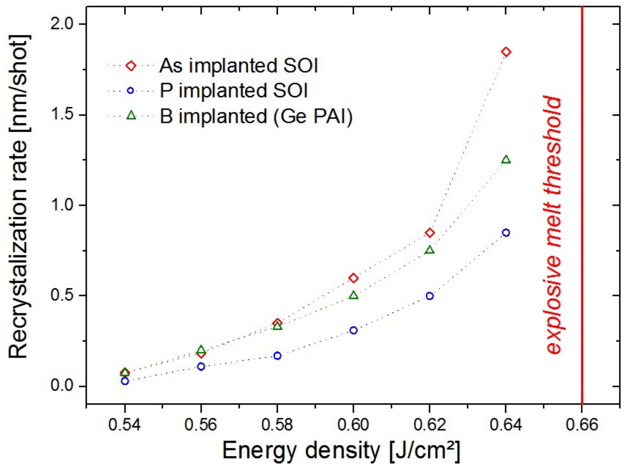

Fig. 5 Recrystallization rate for different energy densities.

4. Conclusions

Starting from SOI layers partially amorphized by implantation, very low thermal budget solid phase recrystallization is possible using a UV nanosecond laser, in a multi-pulse mode, with energy densities just below the melt threshold. Recrystallization rates (nm/pulse) have been easily extracted from time resolved reflectometry data for different energy densities. Electrical activation of dopants will also be studied in the extended paper.

References

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